**Chapter 22 Section 1 Early Astronomy**

**Key Concepts**

* [How does the geocentric model of the solar system differ from the heliocentric model?](javascript:openCrossRef('../ch22/ch22_s1_1.html%23lnk615.3'))
* [What were the accomplishments of early astronomers?](javascript:openCrossRef('../ch22/ch22_s1_2.html%23lnk617.2'))

**Vocabulary**

* [retrograde motion](javascript:openCrossRef('../ch22/ch22_s1_1.html%23lnk616.3'))
* [ellipse](javascript:openCrossRef('../ch22/ch22_s1_2.html%23lnk618.1'))
* [astronomical unit (AU)](javascript:openCrossRef('../ch22/ch22_s1_2.html%23lnk618.6'))
* [astronomy](javascript:openCrossRef('../ch22/ch22_s1_1.html%23lnk614.3'))
* [geocentric](javascript:openCrossRef('../ch22/ch22_s1_1.html%23lnk615.3'))
* [heliocentric](javascript:openCrossRef('../ch22/ch22_s1_1.html%23lnk616.1'))

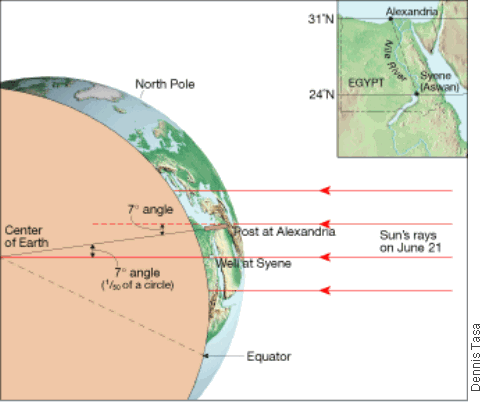
**Ancient Greeks**

[**Astronomy**](javascript:openGlossaryWnd('e_ga_06_astronomy_1a')) is the science that studies the universe. Astronomy deals with the properties of objects in space and the laws under which the universe operates. The “Golden Age” of early astronomy (600 **b.c.**–**a.d.** 150) was centered in Greece. The early Greeks used philosophical arguments to explain natural events. However, they also relied on observations. The Greeks used instruments such as the one in Figure 1. The Greeks developed the basics of geometry and trigonometry. Using these branches of mathematics, they measured the sizes and distances of the sun and the moon.

**Figure 1** *Early astronomers often used instruments called astrolabes to track the positions of the sun and stars.*

The Greeks made many astronomical discoveries. The famous Greek philosopher Aristotle (384–322 **b.c.**) concluded that Earth is round because it always casts a curved shadow on the moon when it passes between the sun and the moon. Aristotle’s belief that Earth is round was largely abandoned in the Middle Ages.

The first successful attempt to establish the size of Earth is credited to Eratosthenes (276–194 **b.c.**). As shown in Figure 2, Eratosthenes observed the angles of the noonday sun in two Egyptian cities that were roughly north and south of each other—Syene (presently Aswan) and Alexandria. Finding that the angles differed by 7 degrees, or 1/50 of a complete circle, he concluded that the circumference of Earth must be 50 times the distance between these two cities. The cities were 5000 stadia apart, giving him a measurement of 250,000 stadia. Many historians believe the stadia was 157.6 meters. This would make Eratosthenes’ calculation of Earth’s circumference—39,400 kilometers—a measurement very close to the modern circumference of 40,075 kilometers.

**Figure 2** *This diagram shows the orientation of the sun’s rays at Syene (Aswan) and Alexandria in Egypt on June 21 when Eratosthenes calculated Earth’s circumference.*

Probably the greatest of the early Greek astronomers was Hipparchus (second century **b.c.**), best known for his star catalog. Hipparchus determined the location of almost 850 stars, which he divided into six groups according to their brightness. He measured the length of the year to within minutes of the modern year and developed a method for predicting the times of lunar eclipses to within a few hours.

**Geocentric Model**

The Greeks believed in the [**geocentric**](javascript:openGlossaryWnd('e_ga_06_geocentric')) view. They thought that Earth was a sphere that stayed motionless at the center of the universe. **In the geocentric model, the moon, sun, and the known planets—Mercury, Venus, Mars, and Jupiter—orbit Earth.** Beyond the planets was a transparent, hollow sphere on which the stars traveled daily around Earth. This was called the celestial sphere. To the Greeks, all of the heavenly bodies, except seven, appeared to remain in the same relative position to one another. These seven wanderers included the sun, the moon, Mercury, Venus, Mars, Jupiter, and Saturn. Each was thought to have a circular orbit around Earth. The Greeks were able to explain the apparent movements of all celestial bodies in space by using this model. This model, however, was not correct. Figure 3A on page 616 illustrates the geocentric model.

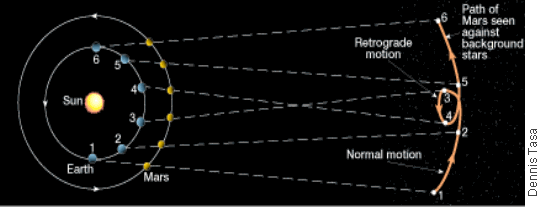
**Heliocentric Model**

Aristarchus (312–230 **b.c.**) was the first Greek to believe in a sun-centered, or [**heliocentric**](javascript:openGlossaryWnd('e_ga_06_heliocentric')), universe. **In the heliocentric model, Earth and the other planets orbit the sun.** Aristarchus used geometry to calculate the relative distances from Earth to the sun and from Earth to the moon. He later used these distances to calculate the size of the sun and the moon. But Aristarchus came up with measurements that were much too small. However, he did learn that the sun was many times more distant than the moon and many times larger than Earth. Though there was evidence to support the heliocentric model, as shown in Figure 3B, the Earth-centered view, shown in Figure 3A, dominated Western thought for nearly 2000 years.

**Ptolemaic System**

Much of our knowledge of Greek astronomy comes from Claudius Ptolemy. In a 13-volume work published in **a.d.** 141, Ptolemy presented a model of the universe that was called the Ptolemaic system. It accounted for the movements of the planets. The precision with which his model was able to predict the motion of the planets allowed it to go unchallenged for nearly 13 centuries.

Just like the Greeks, Ptolemy’s model had the planets moving in circular orbits around a motionless Earth. However, the motion of the planets against the background of stars seemed odd. Each planet, if watched night after night, moves slightly eastward among the stars. Periodically, each planet appears to stop, reverse direction for a time, and then resume an eastward motion. The apparent westward drift is called [**retrograde motion**](javascript:openGlossaryWnd('e_ga_06_retrogrdmotn')) and is diagrammed in Figure 4 on page 617. This rather odd apparent motion results from the combination of the motion of Earth and the planet’s own motion around the sun, as shown in Figure 4.

It is difficult to accurately represent retrograde motion by using the Earth-centered model. Even though Ptolemy used the wrong model, he was able to account for the planets’ motions.

**Figure 4 Retrograde Motion** *When viewed from Earth, Mars moves eastward among the stars each day. Then periodically it appears to stop and reverse direction. This apparent movement, called retrograde motion, occurs because Earth has a faster orbital speed than Mars and overtakes it.*

**The Birth of Modern Astronomy**

The development of modern astronomy involved a break from previous philosophical and religious views. Scientists began to discover a universe governed by natural laws. We will examine the work of five noted scientists: Nicolaus Copernicus, Tycho Brahe, Johannes Kepler, Galileo Galilei, and Sir Isaac Newton.

**Nicolaus Copernicus**

For almost 13 centuries after the time of Ptolemy, very few astronomical advances were made in Europe. The first great astronomer to emerge after the Middle Ages was Nicolaus Copernicus (1473–1543) from Poland. Copernicus became convinced that Earth is a planet, just like the other five planets that were known. The daily motions of the heavens, he reasoned, could be better explained by a rotating Earth.

**Copernicus concluded that Earth is a planet. He proposed a model of the solar system with the sun at the center.** This was a major break from the ancient idea that a motionless Earth lies at the center. Copernicus used circles, which were considered to be the perfect geometric shape, to represent the orbits of the planets. However, the planets seemed to stray from their predicted positions.

**Tycho Brahe**

Tycho Brahe (1546–1601) was born of Danish nobility three years after the death of Copernicus. Brahe became interested in astronomy while viewing a solar eclipse that had been predicted by astronomers. He persuaded King Frederick II to build an observatory near Copenhagen. The telescope had not yet been invented. At the observatory, Brahe designed and built instruments, such as the angle-measuring device shown in Figure 5. He used these instruments for 20 years to measure the locations of the heavenly bodies. **Brahe’s observations, especially of Mars, were far more precise than any made previously.** In the last year of his life, Brahe found an able assistant, Johannes Kepler. Kepler kept most of Brahe’s observations and put them to exceptional use.

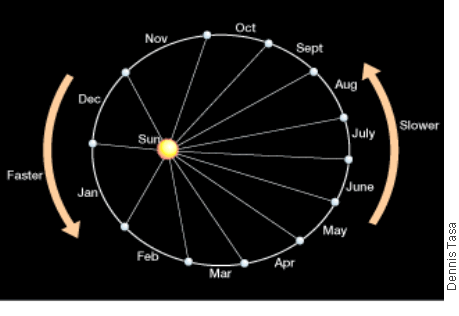
**Figure 5 Tycho Brahe in His Observatory** *Brahe (central figure) is painted on the wall within the arc of a sighting instrument called a quadrant.*

**Johannes Kepler**

Copernicus ushered out the old astronomy, and Johannes Kepler (1571–1630) ushered in the new. Kepler had a good mathematical mind and a strong faith in the accuracy of Brahe’s work. **Kepler discovered three laws of planetary motion.** The first two laws resulted from his inability to fit Brahe’s observations of Mars to a circular orbit. Kepler discovered that the orbit of Mars around the sun is not a perfect circle. Instead, it is an oval-shaped path called an [**ellipse**](javascript:openGlossaryWnd('e_ga_06_ellipse')). About the same time, he realized that the speed of Mars in its orbit changes in a predictable way. As Mars approaches the sun, it speeds up. As it moves away from the sun, it slows down.

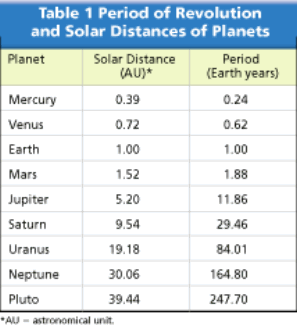
**After decades of work, Kepler summarized three laws of planetary motion**:

1. The path of each planet around the sun is an ellipse, with the sun at one focus. The other focus is symmetrically located at the opposite end of the ellipse.
2. Each planet revolves so that an imaginary line connecting it to the sun sweeps over equal areas in equal time intervals, as shown in Figure 6. If a planet is to sweep equal areas in the same amount of time, it must travel more rapidly when it is nearer the sun and more slowly when it is farther from the sun.
3. The square of the length of time it takes a planet to orbit the sun (orbital period) is proportional to the cube of its mean distance to the sun. [p2=a3]

**Figure 6 Planet Revolution** *A line connecting a planet to the sun would move in such a manner that equal areas are swept out in equal times. Thus, planets revolve slower when they are farther from the sun and faster when they are closer.*

In its simplest form, the orbital period of revolution is measured in Earth years. The planet’s distance to the sun is expressed in astronomical units. The [**astronomical unit (AU)**](javascript:openGlossaryWnd('e_ga_06_astronmclunt')) is the average distance between Earth and the sun. It is about 150 million kilometers.

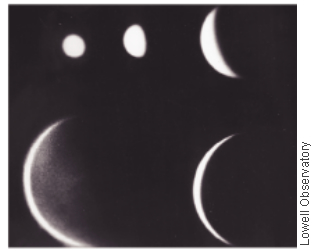
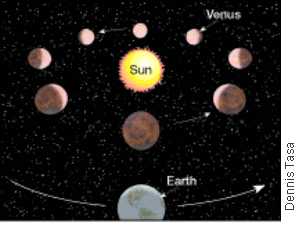
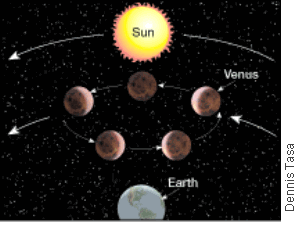
Using these units, Kepler’s third law states that the planet’s orbital period squared is equal to its mean solar distance cubed (P2 = a3). Therefore, the solar distances of the planets can be calculated when their periods of revolution are known. For example, Mars has a period of 1.88 years, which squared equals 3.54. The cube root of 3.54 is 1.52, and that is the distance to Mars in astronomical units shown in Table 1.



**Galileo Galilei**

Galileo Galilei (1564–1642) was the greatest Italian scientist of the Renaissance. **Galileo’s most important contributions were his descriptions of the behavior of moving objects.** All astronomical discoveries before his time were made without the aid of a telescope. In 1609, Galileo heard that a Dutch lens maker had devised a system of lenses that magnified objects. Apparently without ever seeing a telescope, Galileo constructed his own. It magnified distant objects to three times the size seen by the unaided eye.

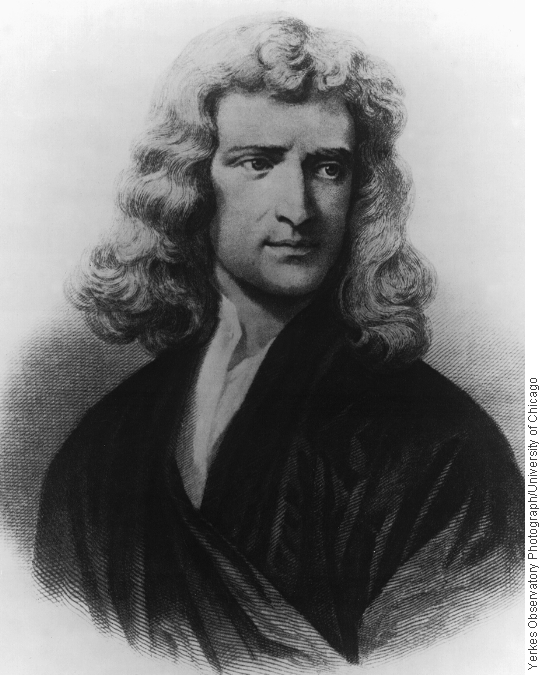
Using the telescope, Galileo was able to view the universe in a new way. He made many important discoveries that supported Copernicus’s view of the universe, such as the following:

* *The discovery of four satellites, or moons, orbiting Jupiter.* This proved that the old idea of Earth being the only center of motion in the universe was wrong. Here, plainly visible, was another center of motion—Jupiter. People who opposed the sun-centered system said that the moon would be left behind if Earth really revolved around the sun. Galileo’s discovery disproved this argument.
* *The discovery that the planets are circular disks, not just points of light, as was previously thought.* This showed that the planets must be Earth-like.
* *The discovery that Venus has phases just like the moon.* So Venus orbits its source of light—the sun. Galileo saw that Venus appears smallest when it is in full phase and therefore farthest from Earth, as shown in Figure 7.

**Figure 7 Relating Cause And Effect** *In the geocentric model, which phase of Venus would be visible from Earth?*

* *The discovery that the moon’s surface was not smooth. Galileo saw mountains, craters, and plains. He thought the plains might be bodies of water. This idea was also believed by others, as we can tell from the names given to these features (Sea of Tranquility, Sea of Storms, and so forth).*
* *The discovery that the sun had sunspots, or dark regions.* Galileo tracked the movement of these spots and estimated the rotational period of the sun as just under a month.

**Sir Isaac Newton**

Sir Isaac Newton (1642–1727) was born in the year of Galileo’s death. See Figure 8. Many scientists had attempted to explain the forces involved in planetary motion. Kepler believed that some force pushed the planets along in their orbits. Galileo correctly reasoned that no force is required to keep an object in motion. And he proposed that a moving object will continue to move at a constant speed and in a straight line. This concept is called inertia.

**Figure 8** *Sir Isaac Newton*

The problem, then, was not to explain the force that keeps the planets moving but rather to determine the force that keeps them from going in a straight line out into space. At the age of 23, Newton described a force that extends from Earth into space and holds the moon in orbit around Earth. **Although others had theorized the existence of such a force, Newton was the first to formulate and test the law of universal gravitation.**

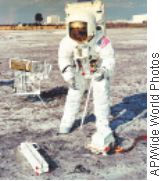
**Universal Gravitation**

According to Newton, every body in the universe attracts every other body with a force that is directly proportional to their masses and inversely proportional to the square of the distance between their centers of mass.

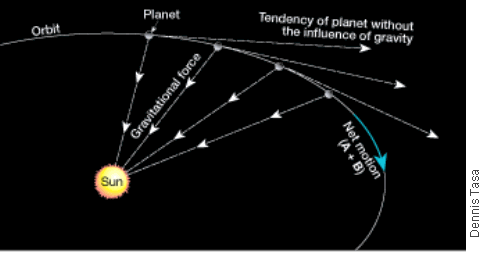
The gravitational force decreases with distance, so that two objects 3 kilometers apart have 32, or 9, times less gravitational attraction than if the same objects were 1 kilometer apart.

The law of universal gravitation also states that the greater the mass of the object, the greater is its gravitational force. For example, the mass of the moon creates a gravitational force strong enough to cause ocean tides on Earth. But the tiny mass of a satellite has no measurable effect on Earth. The mass of an object is a measure of the total amount of matter it contains. But more often mass is measured by finding how much an object resists any effort to change its state of motion.

Often we confuse the concept of mass with weight. Weight is the force of gravity acting upon an object. Weight is properly expressed in newtons (N). Therefore, weight varies when gravitational forces change. See Figure 9.

**Figure 9** Weight is the force of gravity acting on an object. **A** An astronaut with a mass of 88 kg weighs 863 N on Earth. **B** An astronaut with a mass of 88 kg weighs 141 N on the moon. **Calculating** If the same astronaut stood on Mars where the acceleration due to gravity is about 3.7 m/s2, how much would the astronaut weigh?

Newton proved that the force of gravity, combined with the tendency of a planet to remain in straight-line motion, results in the elliptical orbits that Kepler discovered. Earth, for example, moves forward in its orbit about 30 kilometers each second. During the same second, the force of gravity pulls it toward the sun about 0.5 centimeter. Newton concluded that it is the combination of Earth’s forward motion and its “falling” motion that defines its orbit. As Figure 10 shows, if gravity were somehow eliminated, Earth would move in a straight line out into space. If Earth’s forward motion suddenly stopped, gravity would pull it directly toward the sun.

**Figure 10** *Without the influence of gravity, planets would move in a straight line out into space.*

Newton used the law of universal gravitation to redefine Kepler’s third law, which states the relationship between the orbital periods of the planets and their solar distances. When restated, Kepler’s third law takes into account the masses of the bodies involved and provides a method for determining the mass of a body when the orbit of one of its satellites is known.

**SECTION 22.1 Assessment**

**Reviewing Concepts**

(1)Compare and contrast the geocentric and heliocentric models of the universe.

(2)What produces the retrograde motion of Mars?

(3)What geometric arrangements did Ptolemy use to explain retrograde motion?

(4)What major change did Copernicus make in the Ptolemaic system? Why was this change significant?

**Critical Thinking**

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(6) **Summarizing** Summarize Kepler’s three laws of planetary motion.

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